LEVEL II

MOSI Project — 3

Sonar Target Classification

DALMO VICTOR

BELMONT, CALIFORNIA

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(6) SONAR TARGET CLASSIFICATION.

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Prepared by : Dalmo Victor Company
Division of Textron Inc.
Belmont, California

Richard E. Baker
Richard E. Baker
Electronics Consultant

R. D. Murie
R. D. Murie
Chief Engineer

(14) R-2850-3062

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I. CONCLUSIONS AND RECOMMENDATIONS

It appears that rapid classification can be provided during detection by the employment of high resolution techniques and optimum methods of displaying resolution information. A high resolution technique could be supplemented with the ASPECT or other techniques to provide more positive identification in the time allowed in tactical situations.

A hybrid FM-pulse compression solution appears to be optimum for implementing the high resolution technique.

It would be difficult to determine the range resolution required to give an acceptable probability of classification under tactical conditions without experimental data.

The resolution that existing sonar equipments are capable of producing is limited by their transducer characteristics. It is felt that existing equipment can be modified to provide good enough resolution to provide proof of feasibility and experimental evaluation of the probability of the classification of submarine targets for a variety of conditions.

It is recommended that an experimental and study program be instituted

to provide: (1) modified existing equipment capable of being used to evaluate the potential of the high resolution technique, (2) an experimental measure of the probability of the classification of submarine targets, and (3) further theoretical study, supplemented by the experimental results, of the classification problem.

II. INTRODUCTION

Classification of the physical properites of sonar targets is difficult with conventional sonar techniques. The signals scattered from schools of fish and other objects can appear to be similar to those scattered by submarines. The employment of the ASPECT technique to identify submarines requires relatively long periods of time to achieve the correlation required for positive identification (typically 2 minutes). Identification from the range rate of targets also takes considerable time. The amplitude modulation of the scattered signals produced by propellers does not provide a very dependable method for discrimination. It is felt that a considerable increase in the probability of identifying submarines with a single detection pulse can be obtained with existing equipment by utilizing high range resolution techniques, optimum signal processing and display methods. By decreasing the probability of false alarms for short periods of time, dependable classification should be possible for realistic tactical situations.

The bladders of fish are their primary scatterers. The statistical distribution of scatterers in a school will be random for any sequence of range cells. The intensity of the signal scattered from schools of fish will, therefore, have zero correlation between resolvable sonar range cells. If the sonar range resolution is smaller than the extent

in range of primary scattering surfaces on a submarine, it can be expected that the submarine echoes received from adjacent cells will have a high degree of correlation. This discrete scattering difference may be utilized to identify targets. It is desirable to achieve as small a resolvable range increment as possible to discriminate between fish and submarines, in short periods of time.

The target information should be displayed on a presentation that has a wide dynamic range. A wide dynamic range reduces the increment of signal amplitudes that would appear to have equal displayed magnitudes so that the probability of false alarms due to the occurance of equal displayed signal magnitudes in adjacent cells, for uncorrelated signals, would be small. The displayed range should be small enough in extent so that each resolvable sonar range cell can be clearly discerned. It is felt that the primary high resolution classification display should be an "A" type presentation. It would be possible to display a few hundred discernible range elements on such a display.

A method that appears to be reasonable for classification consists of the following. A low resolution display (PPI) could be employed to determine the targets to be classified. Cursorily positioned gates could provide the signals, for reasonable range increments, that are displayed on "A" type displays or recorders. The high resolution "A"

type presentation should provide the facility for rapidly eliminating a large percentage of the false targets. The high resolution display should also provide positive identification for submarines in a large percentage of the cases that would be encountered. In the event that a suspicious target could not be positively classified, time may be available for supplemental classification by the use of the ASPECT highlight clue and other time dependent techniques.

The best range resolution that can be achieved with any sonar system is completely determined by its overall bandwidth, not necessarily the pulse length. The bandwidth of sonar equipment is limited primarily by transducer characteristics. Typical transducers in existing equipments have Q's of approximately 10. The best range resolution that could be obtained under these conditions would be approximately 1.7 feet with a resonant frequency of 10Kc, and 5 feet at a resonant frequency of 3.5 Kc. The actual resolution that could be achieved in operation will probably be larger than that determined solely by transducer characteristics. The resolution that could be achieved in practice, with existing equipment, may be adequate to provide classification by resolution under some conditions, but a considerable improvement could be obtained with a system employing a wide band transducer. A wide band, high efficiency, transducer has been developed at the U.S. Navy Underwater Sound Reference Laboratory.

FM and pulse compression techniques are employed to increase the radiated energy, for a given bandwidth, while keeping the peak power below the level that would produce cavitation. The same resolution can be obtained with FM or pulse compression techniques, for a given bandwidth.

The requirements of the high resolution classification mode of operation can be satisfied optimally, from an operational point of view, by a hybrid of FM and pulse compression techniques.

The system that is discussed in the Appendix utilizes a relatively small number of FM channels and a delay type spectrum analyzer to provide a large number of high resolution range elements. A magnetic drum is employed as the data processor. The multiple FM channels are employed to reduce the performance required from the processor so that delay precision, bandwidth, and dynamic range requirements can be easily satisfied with a magnetic drum.

The hybrid system is a relatively simple system that provides the required range resolution, number of range elements, and time sequential readout.

III. RESOLUTION REQUIREMENTS

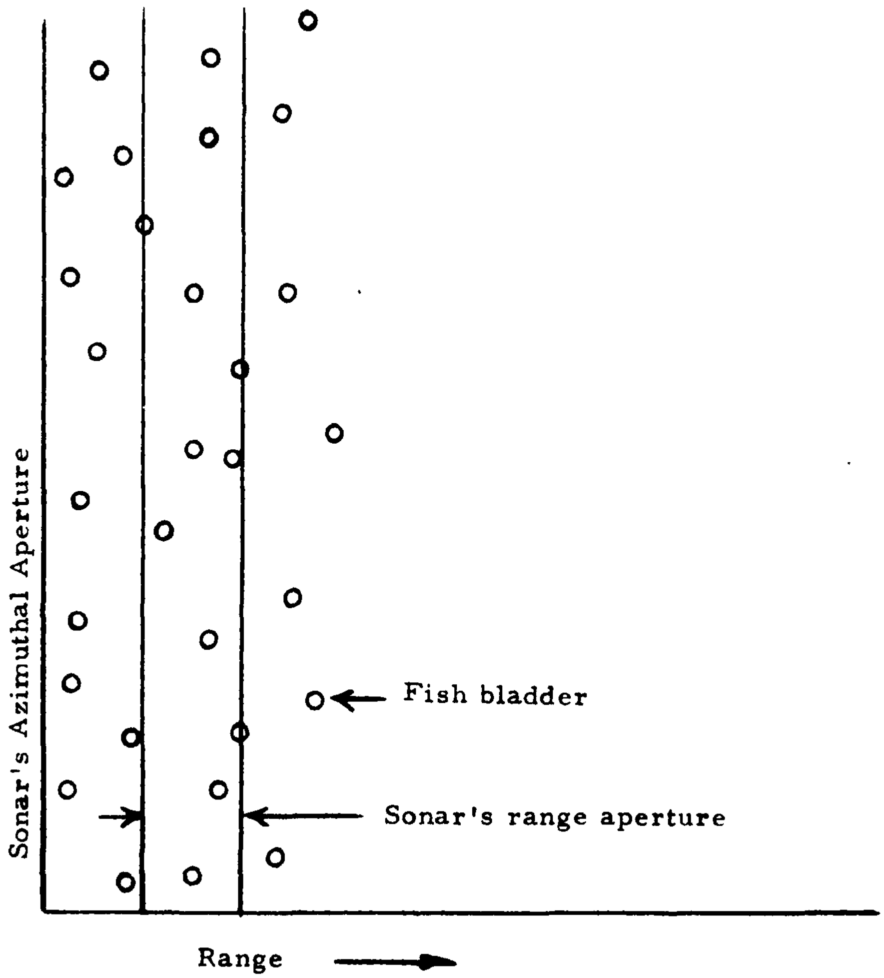
The choice of the effective resolution required for the identification of the signals received from submarines, as compared to those received from schools of fish, can be qualitatively evaluated by comparing the back scattering properties of natural and man made objects.

The primary scatterer of a fish is its bladder. When schools of fish are illuminated by a sonar, the probability is high that a large number of scatterers will be present in a resolvable sonar range cell, for conventional sonar beamwidths. For example, a 10 degree sonar beamwidth would have an arc length of approximately 1000 feet at a range of 1 n.m.

Figure 1 shows a hypothetical distribution of fish within a number of resolvable sonar elements (not to scale).

The signal received from any one resolvable sonar element is the vector summation of the signals from the scatterers in that element. The signals from different cells are separable.

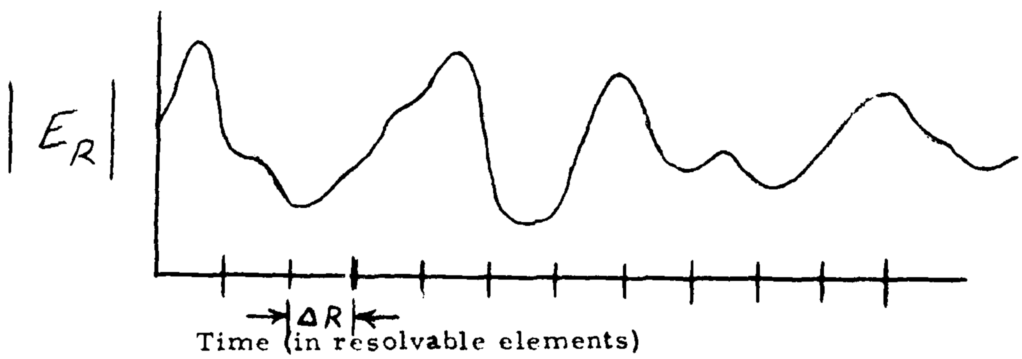
It will be assumed that the width of a range cell is more than one-half of a sonic wavelength (the wavelength of a sonic signal with a frequency of



Hypcthetical Fish Distribution

FIGURE 1

5 Kc would be approximately 1 foot). The scatterers are randomly distributed over the area (as opposed to well ordered distributions). The signal received from the scatterers in a range cell will be the vector sum of a large number of independent components. The sum will have a two dimensional normal probability distribution. The absolute magnitude of the sum will have a Rayleigh probability distribution. The signals received from separate cells will be statistically independent so that their amplitude is an uncorrelated random variable. The probability of any specific increment of signal amplitude occuring in a cell can be determined from a Rayleigh probability distribution. The probability of the occurance of similar amplitudes in adjacent range cells would be the product of their individual probabilities. A typical sonar signal received from a school of fish is shown in Figure 2.



Signal from School of Fish

FIGURE 2

The signals that are scattered from small increments of range from the surface of a submarine are relatively well ordered because of its orderly structural characteristics. If the range resolution of the sonar system is smaller than the extent in sonar range of primary scattering surfaces on the submarine, it can be expected that the signals received from adjacent cells will exhibit a high degree of correlation. The important clue here is not resolution of individual scatterers, as with ASPECT, but the orderly scattered vector sum intensity in adjacent range cells from a submarine versus marine life.

Figure 3 is a sketch of the scattering geometry for a conning tower at quarter aspect. The shaded area represents the area illuminated in a resolvable range increment. The echo received from this range cell can be approximated by that received from a rectangular flat plate of the strip's size.

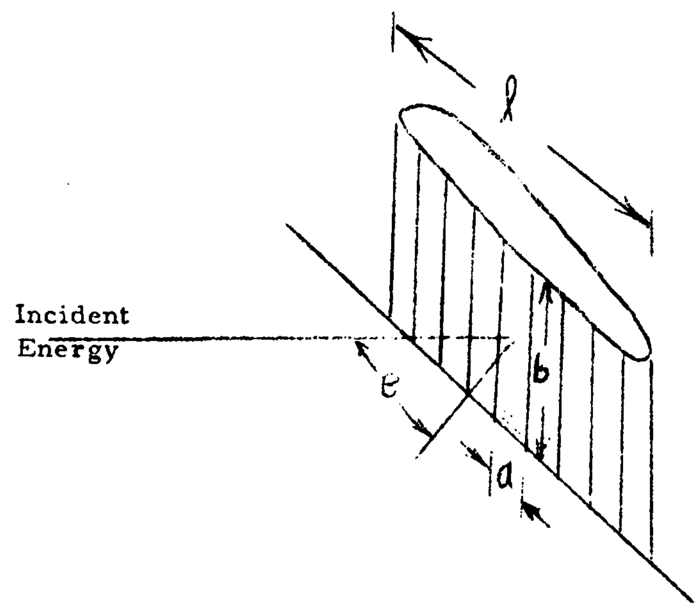
When the dimension "a" is several wavelengths (physical optics case) and the long dimension of the strip is normal to the direction of propagation, the energy received from the strip is proportional to,

$$P_R \sim 4\pi \left(\frac{ab}{\lambda}\right)^2 \cos^2\theta \left[\frac{\sin(ka\sin\theta)}{ka\sin\theta}\right]^2$$

where $k = \dfrac{2\pi}{\lambda}$

if ΔR = the sonar's range resolution

$$a = \frac{\Delta R}{\sin\theta}$$



Conning Tower Scattering Geometry (Quarter Aspect)

FIGURE 3

so that

$$P_R \sim \frac{4\pi}{\tan^2\theta}\left(\frac{b^2 \Delta R^2}{\lambda^2}\right)\left[\frac{\sin(k\Delta R)}{k\Delta R}\right]^2$$

When the angle θ approaches zero, it is obvious that the echoing area cannot exceed,

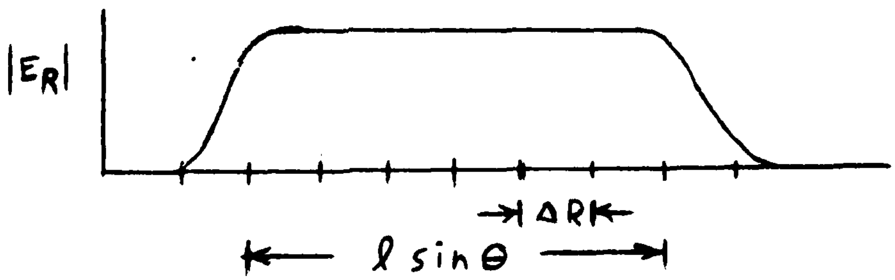
$$P_N = \frac{4\pi A^2}{\lambda^2}$$

Where A = The physical area of the tower

Near beam aspect, the scattered signal will have the conventional interference type of lobe structure.

When the range extent of the surface is more than a sonar resolution cell, the signals received from resolvable strips, with similar aspects, should have approximately the same amplitude.

A sketch of the type of signal that could be expected to be received from the conning tower is shown in Figure 3.



Conning Tower Signal (Quarter Aspect)
FIGURE 3

At beam and bow aspects, the high light scattering surfaces will have smaller range extents so that their signals would occupy fewer range cells.

It would be desirable to have as small a range resolution cell as 1/2 wave length to produce a significant difference in the correlation of the signals, during the echo time, between fish and submarine returns.

The number of highlights and spacings that are observed at beam and bow aspects, should be well enough defined from a priori information to provide a low probability of false alarm.

IV. TRANSDUCER TRANSFER CHARACTERISTICS

The best range resolution that can be achieved with a sonar system is completely determined by the effective bandwidth of the system, not necessarily the pulse length of transmission. Schemes can be employed to code the phase of the transmitted signal so that its duration is many times longer than the minimum pulse duration that can be achieved with a specified bandwidth. FM and pulse compression systems employ such techniques to increase the energy that can be transmitted, when there are limitations on the peak power that can be transmitted. The signals are decoded upon reception. The best resolution is obtained with a linear phase versus frequency spectral characteristic and is inversely proportional to the bandwidth of the system.

The bandwidth of sonar equipment is primarily determined by transducer characteristics. Transducers in existing sonar equipment have relatively small bandwidths. While their bandwidths may be adequate to provide classification by resolution under some conditions, a considerable improvement could be obtained with a system employing a wider band transducer. A wide band, high efficiency, transducer has been developed at the U. S. Navy Underwater Sound Reference Laboratory. A discussion of its characteristics is presented in Reference 1.

A typical value for the Q's of transducers in existing sonar equipment is 10. Their mechanical bandpass characteristics are similar in shape to a single tuned circuit. The voltage response of a single tuned circuit, as a function of frequency, is proportional to:

$$E \sim \frac{1}{\sqrt{1 + \frac{4(f - f_0)^2}{\beta^2}}}$$

where

$$\beta = \frac{f_0}{Q} = \text{the 3 db bandwidth of the circuit}$$

$$f_0 = \text{the resonant frequency of the transducer.}$$

The overall frequency response of the system would be proportional to the square of this quantity if the receiving and transmitting transducers have the same Q.

It will be assumed that the optimum overall spectral characteristic that can be obtained under the circumstances is the same as the overall transducer frequency response characteristic.

This characteristic can be approximated with a Gaussian type of function, to simplify subsequent Fourier transformations. The use of the Gaussian type of function will result in a slightly pessimistic estimate of the actual resolution that can be achieved. It also will be assumed that the linearity of the phase characteristic of practical circuits would not be significantly different from the ideal phase characteristic.

The assumed transducer characteristic is:

$$T(f-f_0) = e^{-\frac{\pi^2(f-f_0)^2}{K^2}}$$

$$T(f-f_0) = \frac{1}{\sqrt{2}} \quad \text{when } f-f_0 = \frac{\beta}{2}$$

Then,

$$\frac{\pi^2\beta^2}{K^2 4} = 0.346$$

or,

$$K^2 = 7.15\beta^2$$

so,

$$T(f-f_0) = e^{-\frac{\pi^2(f-f_0)^2}{7.15\beta^2}}$$

The overall spectral characteristic would be the square of this quantity, or:

$$U(f-f_0) = e^{-\frac{\pi^2(f-f_0)^2}{3.58\beta^2}}$$

The Fourier transform of this expression is:

$$\mathcal{F}\left[U(f-f_0)\right] = u_1(t)\cdot e^{j2\pi f_0 t}$$

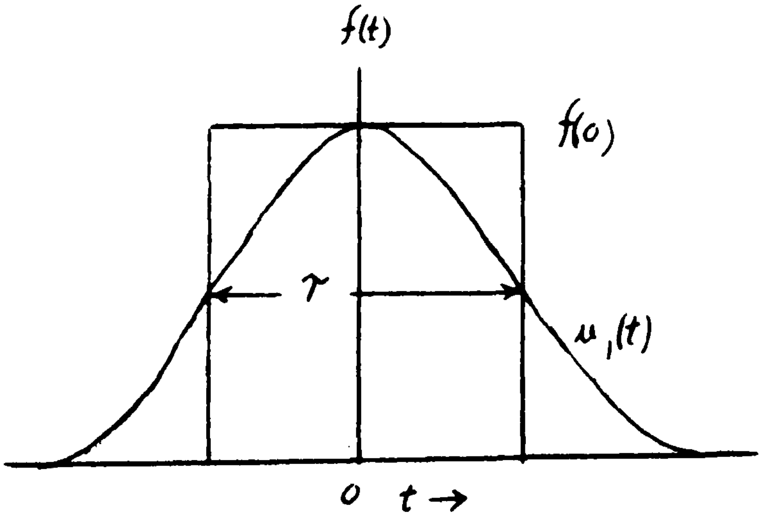
where

$$u_1(t) = \mathcal{F}\left[e^{-\frac{\pi^2 f^2}{K^2}}\right]$$

$$u(t) = \frac{K}{\sqrt{\pi}}\, e^{-K^2t^2}\cdot e^{j2\pi f_0 t}$$

$$u(t) = \frac{2.67\beta}{\sqrt{\pi}}\, e^{-7.15\beta^2t^2}\cdot e^{j2\pi f_0 t}$$

The first term on the right of this equation represents the amplitude modulation envelope. An equivalent pulse width can be determined from a commonly accepted criteria. The equivalent pulse width will be defined as the width of a rectangular pulse having the same peak height and area as the original pulse. Figure 1 is a sketch of the original pulse and its equivalent rectangular pulse.



Original Pulse and Equivalent Rectangular Pulse

FIGURE 1

The width of the rectangular pulse is the integral of the original pulse divided by its value at t = 0, or:

$$\tau = \int_{-\infty}^{\infty} e^{-7.15\beta^2 t^2}\, dt$$

Since

$$\int_{-\infty}^{\infty} e^{-a^2 x^2}\, dx = \frac{\sqrt{\pi}}{a}$$

$$\tau = \frac{\sqrt{\pi}}{2.67\beta} = \frac{1}{1.5\beta}$$

This can also be expressed as:

$$\tau = \frac{Q}{1.5 f_o} \qquad \tau > \frac{\lambda}{v} = \frac{1}{f_o}$$

Since the sonar range resolution is equal to:

$$\Delta R = \frac{v\tau}{2}$$

where, v = the velocity of sonic propagation

$$\Delta R = \frac{vQ}{3 f_o} \qquad \Delta R > \frac{\lambda}{2}$$

With a transducer Q of 10, at a center frequency of 10 kc, the best range resolution that could be achieved would be approximately 1.7 feet. At 3.5 kc, the best range resolution would be approximately 5 feet.

V. FM AND PULSE COMPRESSION TECHNIQUES

The detection range of a sonar is a function of the transmitted energy. The peak power that a sonar transducer can radiate is limited to a value below that required to generate cavitation. FM and pulse compression techniques offer means of increasing the radiated energy, for a given bandwidth, and range resolution without producing cavitation.

The best range resolution that can be achieved with any sonar system is completely determined by its overall bandwidth, not necessarily the duration of transmission. A linear phase versus frequency spectral characteristic generates the shortest pulse that can be produced for a given bandpass characteristic. FM and pulse compression techniques employ phase modulation of the transmitted signal to increase its time duration to many times that of the shortest pulse that could be generated for a given bandwidth. The phase dispersion(non-linear phase modulation) is removed on reception so that a short pulse is produced at the receiver's output.

An FM system performs the decoding in the frequency domain. It requires a separate channel, in the receiver, for each range cell. A CHIRP pulse compression system performs the decoding in both the

time and frequency domains. It requires only one receiver channel to provide target information for the entire listening time.

Since the same range resolution can be achieved with both systems, for a given bandwidth, the method employed to achieve high range resolution would be dictated by the requirements of the specific problem.

The classification of targets by the use of high range resolution precludes the display of sonar information for large range increments. The sonar range increment presented on a classification display should probably be limited to several hundred resolvable sonar elements, for a displayed range from approximately 500 to 1500 feet.

The requirements for the classification display's range base can be easily satisfied, in theory, with an FM system.

Sonar equipments are available that have the FM mode of operation. The need for several hundred receiver filters for the required number of range elements could be obviated relatively simply with a delay type of spectrum analyzer. A description of a system that is a hybrid of the FM and pulse compression techniques is presented in the Appendix.

The existing FM transmitting equipr. nt should have characteristics that are adequate for proof of feasibility of the high resolution classification mode of operation.

APPENDIX

Spectrum Analyzer Type FM Sonar

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APPENDIX

Spectrum Analyzer Type FM Sonar

In a FM sonar system, the received signal is heterodyned with a duplicate of the transmitted signal, that may be delayed in time, so that the frequency of the components of the heterodyned signal are associated with specific sonar ranges.

The transmitted signal can be expressed as,

$$e_T = \mu_1(t) \cdot \cos 2\pi \left[f_0 t + \frac{K t^2}{2} \right]$$

where,

$\mu_1(t)$ = The transmitted pulse envelope, centered at t = 0.

f_0 = The carrier frequency of the transmitted signal.

The received signal is,

$$e_R = \sum_{m=0}^{N} a_m \mu_1\left[(t-\beta) - \tau_m\right] \cos 2\pi \left\{ f_0\left[(t-\beta) - \tau_m\right] + \frac{K\left[(t-\beta) - \tau_m\right]^2}{2} \right\}$$

where,

β = The time delay to the start of the sonar range interval of interest

τ_m = The delay of targets from the beginning of the range interval.

α_m = The relative amplitude of the returns.

The reference signal can be represented as,

$$e_{LO} = u_2(t-\beta) \cos 2\pi \left[f_o(t-\beta) + \frac{K(t-\beta)^2}{2} \right]$$

The heterodyning process forms the product of the received and reference signal. The local oscillator signal has a longer duration than the transmitted signal to prevent duty cycle variation of the desired signals over the range interval of interest.

The argument of the heterodyned signal will be equal to the difference of the received and reference signal arguments. (The sum and image frequencies are rejected in the receiver). The difference of the two arguments is,

$$\theta_D = 2\pi \left\{ f_o \tau_m + \frac{K}{2} \left[2\tau_m (t-\beta) - \tau_m^2 \right] \right\}$$

For stationary targets, the instantaneous frequency of the argument is,

$$f_d = K \tau_m$$

The heterodyned signal can be expressed as,

$$e_D = \sum_{m=0}^{N} a_m u_1 (t - \beta - \tau_m) \cos (2\pi k \tau_m + \phi_m)$$

where,

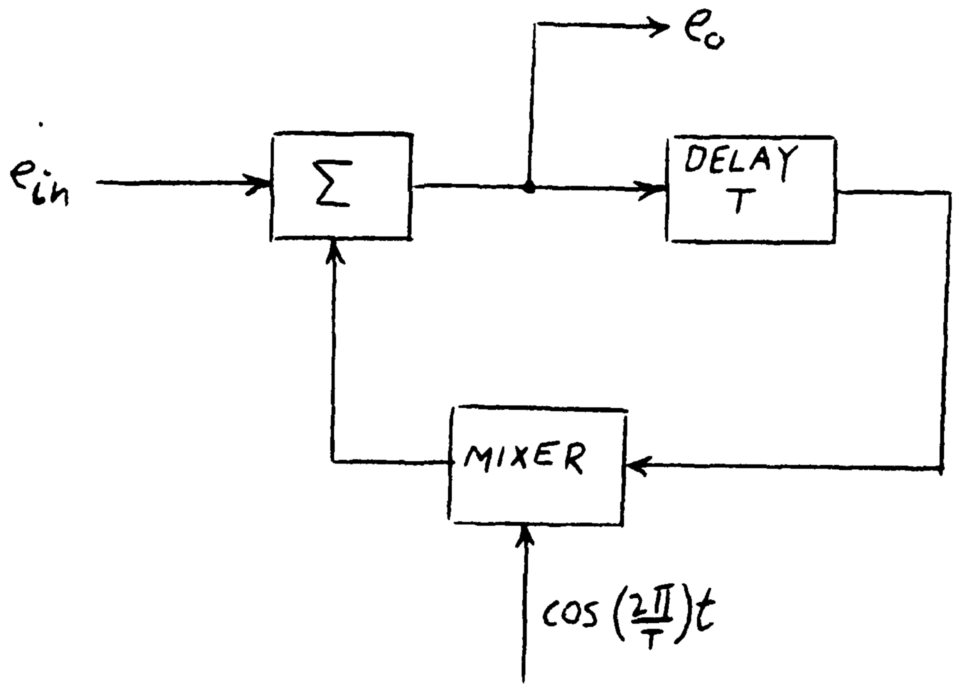
$$\phi_m = f_0 \tau_m - k \tau_m \beta - \frac{k}{2} \tau_m^2$$

The heterodyned signal consists of components whose frequencies are determined from the sonar echoing time of the targets.

Spectrum analysis of the heterodyned signal, to determine the sonar range of the targets, is commonly performed by banks of band pass filters. The requirement for a capacity of hundreds of range resolution cells makes the use of a delay type spectrum analyzer attractive. The delay type spectrum analyzer can synthesize thousands of filters relatively simply.

The theory of delay-line filter type spectrum analyzers is discussed in Reference 2. It is felt that the particular method of implementing the technique that is discussed in the reference is not optimum for the classification problem. The stringent requirements placed on a delay line by this method of implementation can be circumvented by other methods that will be discussed later.

Figure 1 is a block diagram of a delay type spectrum analyzer. The input signal is delayed and stepped up in frequency by the mixer. The mixer is a single side band type so that the carrier and lower side band are cancelled.



Delay Type Spectrum Analyzer

FIGURE 1

The delayed signal is added to the input signal and recirculated around the loop. After N recirculations, the detected output signal is displayed for T seconds. The displayed signal presents the amplitude of the spectrum of the input signal.

As shown in Reference 2, the response characteristic of the analyzer can be determined as follows. The input signal can be expressed as,

$e_i = \cos(\omega t + \alpha)$

Let $t = \tau + mT$

where $0 \leq \tau < T$

and T = the loop delay period.

For convenience, the input signal can then be expressed as the sum of terms consisting of consecutive samples of the original signal, spaced by the delay time, so,

$$e_i(t) = \sum_{m=0}^{N} \mu(t - mT) \cos\left[\omega(\tau + mT) + \alpha\right]$$

The input signal is recirculated in the loop and each time its frequency is raised by $\omega_d = \frac{2\pi}{T}$ so that the output during $NT \leq t < (N+1)T$ is,

$$e_{OT} = \mu(t - NT) \sum_{m=0}^{N} \cos\left[\omega\tau + m\omega T + (N-m)\omega_d\tau + \alpha\right]$$

Since

$$\sum_{m=0}^{N} \cos\left[m\delta + \gamma\right] = \frac{\sin\left[\frac{N+1}{2}\delta\right]\cos\left[\frac{N}{2}\delta + \gamma\right]}{\sin\frac{\delta}{2}}$$

Let

$$\gamma = \omega\tau + N\omega_d\tau + \alpha$$

$$\delta = (\omega T - \omega_d \tau)$$

then,

$$e_{OT} = \mu(t - mT)\,\frac{\sin\left[\frac{N+1}{2}(\omega T - \omega_d\tau)\right]}{\sin\left[\frac{1}{2}(\omega T - \omega_d\tau)\right]} \bullet \cos\left[\left(\omega + \frac{N}{2}\omega_d\right)\tau + \frac{N}{2}\omega T + \alpha\right]$$

The peak of the amplitude response of this expression (the second term on the right) occurs when,

$$\omega = \frac{\omega_d\,\tau}{T} + \frac{k\,2\pi}{T}$$

The device functions unambiguously over a frequency range of $\frac{1}{T}$ cps. The resolution is inversely proportional to the period of integration.

The amplitude response characteristic, that was derived, is dependent on the bandwidth of the device being at least $N\omega_d$, the delay time being close to an exact multiple of the reciprocal of f_d over the integrating interval, and the dynamic range being approximately 20 log N, in db. These requirements make the use of sonic delay lines unattractive.

It appears that an optimum solution for operational equipment would be a hybrid system consisting of a few FM channels and a magnetic drum type of spectrum analyzer.

To demonstrate the characteristics of such a system, a hypothetical case will be discussed. It will be assumed that the system has effective spectral signal bandwidth of 1 KC. The best resolution that can be achieved is roughly 2 feet (the precise resolution is not important to this discussion). If it is decided to display 400 resolvable range elements (800 feet), and the transmitted pulse length is 1/2 sec, the bandwidth of interest of the heterodyned signal is from 0 to 640 cps.

To achieve 2 foot resolution, a delay line system would require a loop delay of approximately 1.56 millisec, a phase-advance signal frequency of 640 cps, a loop bandwidth of 205 KC, and a dynamic range of 50 db.

An alternate approach would be to filter the spectrum into a number of adjacent channels to relax the requirement on the delay device.

For example, if the 640 cps spectrum was split into 10 channels with 64 cps bandwidth, it would only be necessary to integrate 32 samples of the signals in each channel to achieve 2 foot resolution. The required loop delay for each channel would be 15.6 milliseconds; the phase-advance signal frequency, 64 cps; the bandwidth, 2 Kc; and the dynamic range, 30 db.

These signal processor requirements could be satisfied optimally with a 10 track magnetic drum. The drum should revolve at a rate of 2 revolutions per second or 120 RPM.

Two heads per track, spaced by a distance of 1/32th of the drum circumference, could provide the required delay. The sonar timing could be generated by, or derived from, the drum drive to maintain synchronization. The processed signals could be read out of the 10 tracks of the drum in sequence, at suitable times after the end of the integration periods for presentation on a display.

The stored information could be left on the drum as long as desired so that it could be read out once every revolution to provide a continuous presentation on a long persistance display tube phosphor.

REFERENCES

1. C. C. Sims and T. A. Heriquez
"Cavity Loaded Piston Resonators"
J. A. S. A. of September 1962.

2. H. J. Bickel "Spectrum Analysis with Delay Line Filters"
I. R. E. WESCON Convention Record, Part 8, August 1959.